Determining the gluon PDF

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Outline

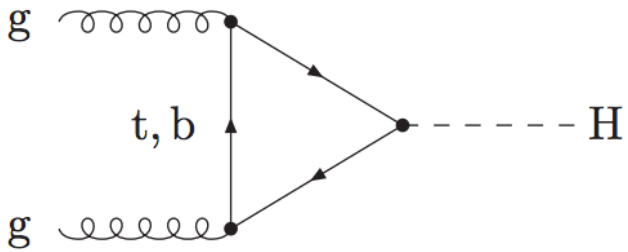
- What are PDFs? Why are they important?
- What do we learn about $g(x, \mu^2)$ from deep inelastic scattering experiments?
- What do we learn about $g(x, \mu^2)$ from hadron-hadron colliders?
- How do we get PDFs from data?

Parton distribution functions

- Parton distribution functions (PDFs) describe the content of the proton
- PDFs depend on:
  - Bjorken x: the fraction of the proton momentum carried by the parton
  - Scale μ^2 (Q^2): what you see inside the proton depends on the energy you probe it with
- The gluon PDF $g(x,\mu^2)$ gives the probability that the proton contains a gluon with momentum fraction x at scale μ^2

Why do we need PDFs?

- To make predictions!
- Example: Higgs production by gluon fusion
  - This is the main production mechanism for a Higgs at the LHC

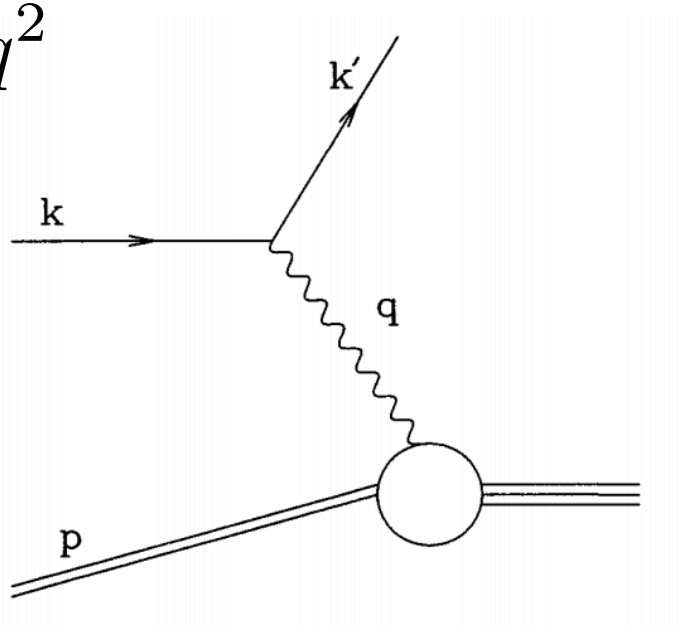


- To calculate the cross section for this process in pp collisions, we need to know the gluon PDF

Deep Inelastic Scattering

- Know p and k (from your beam/target)
- Measure k'
- This is enough to determine all of the following, with $Q^2 = -q^2$

$$
\begin{aligned}
M^2 &= p^2 \\
\nu &= p \cdot q = M(E' - E) \\
x &= \frac{Q^2}{2\nu} = \frac{Q^2}{2M(E - E')} \\
y &= \frac{q \cdot p}{k \cdot p} = 1 - E'/E \ ,
\end{aligned}
$$

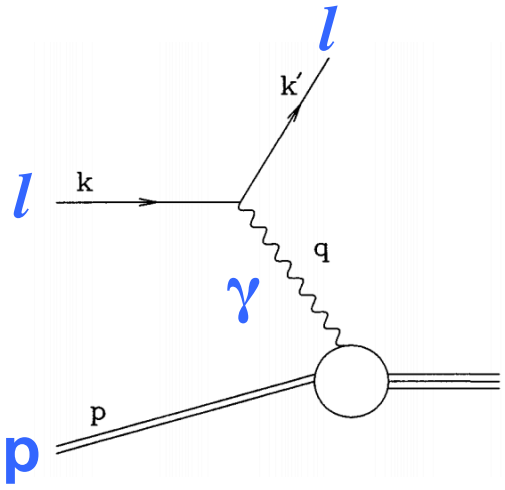


Deep Inelastic Scattering

- Charged lepton scattering

$$lp \to lX$$

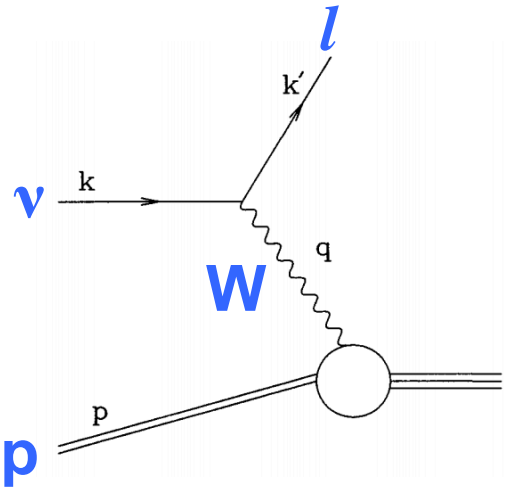
$$\frac{d^2\sigma^{em}}{dxdy} = \frac{8\pi\alpha^2 ME}{Q^4}\left[\left(\frac{1+(1-y)^2}{2}\right)2xF_1^{em} + (1-y)(F_2^{em} - 2xF_1^{em}) - (M/2E)xyF_2^{em}\right]$$



- Neutrino scattering

$$\nu p \to lX$$

$$\frac{d^2\sigma^{\nu(\bar{\nu})}}{dxdy} = \frac{G_F^2 ME}{\pi}\left[(1-y-\frac{M}{2E}xy)F_2^{\nu(\bar{\nu})} + y^2xF_1^{\nu(\bar{\nu})} + (-)\ y(1-\tfrac{1}{2}y)xF_3^{\nu(\bar{\nu})}\right]$$



Deep Inelastic Scattering

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Structure Functions

$$F_i(x, Q^2)$$

Determining PDFs from DIS

- Bjorken limit: $Q^2 \to \infty$
  - In this limit, the parton momentum is parallel to the proton momentum
- The structure functions are sensitive to the quark PDFs

$$F_2^{em}(x) = 2xF_1^{em}(x) = \sum_{q,\bar{q}} e_q^2 xq(x)$$

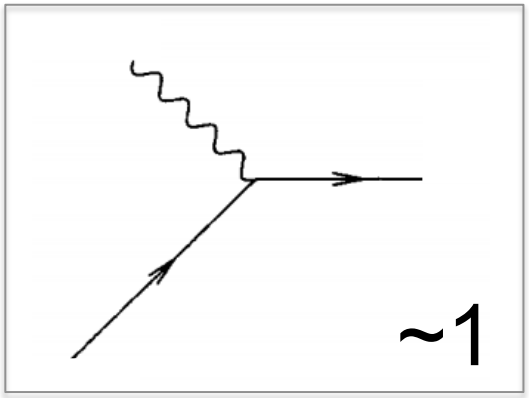
- Can we learn anything about the gluon PDF from these experiments?

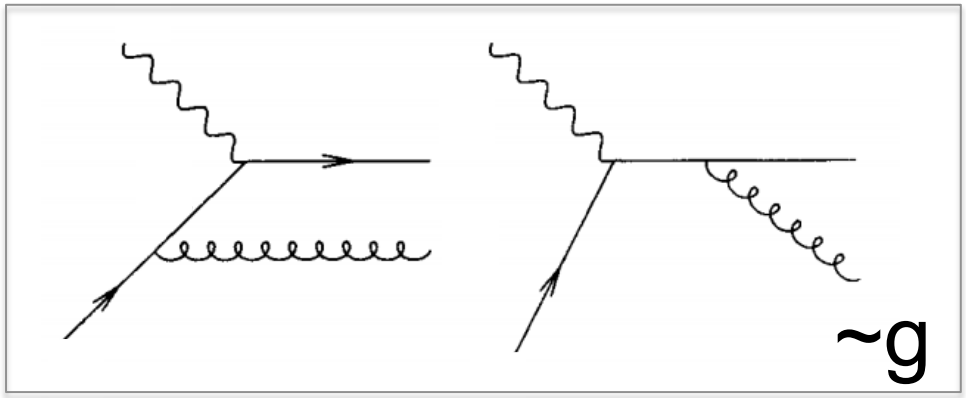
Determining PDFs from DIS

- To learn about the gluon PDF, we must consider higher order in perturbation theory
  - Allow quarks to emit a gluon
- The Bjorken limit no longer applies
  - Gluon emission allows quarks to acquire momentum perpendicular to proton momentum
  - Scaling violation: must consider dependence of structure functions (and PDFs) on Q^2
- Calculate the structure functions to first order in $\alpha_S \sim g^2$ for ep collisions

QCD corrections to DIS

- Contributing diagrams for $\gamma q \rightarrow qX$





QCD corrections to DIS

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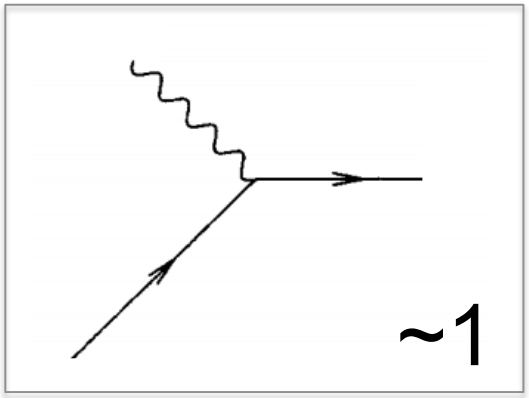
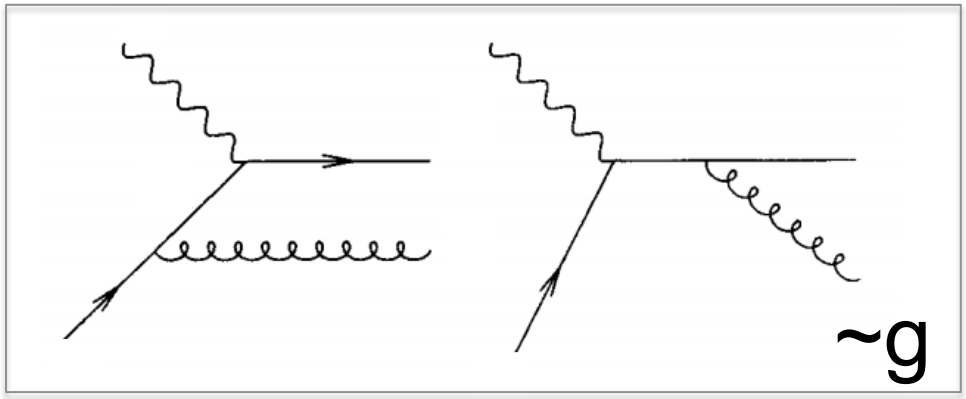
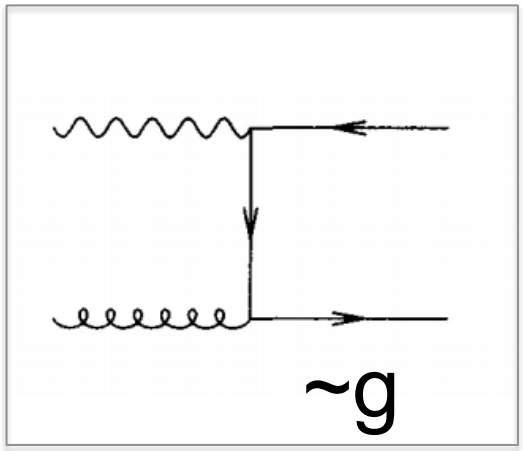




- Contributing diagrams for $\gamma g \rightarrow qX$



Through $\gamma g \rightarrow q\bar{q}$ we are sensitive to the gluon PDF!

QCD corrections to DIS

- Now just do QFT! Or consult a book…
  - R. K. Ellis, W. J. Stirling, and B. R. Webber, *QCD and collider physics*. Cambridge Univ. Press, Cambridge, UK, 1996.
- Find for electron-proton scattering:

$$F_2(x,Q^2) = x\sum_{q,\bar{q}} e_q^2 \int_x^1 \frac{d\xi}{\xi} q(\xi,Q^2) \left\{\delta(1-\frac{x}{\xi}) + \frac{\alpha_S}{2\pi} C_q^{\overline{\rm MS}}\left(\frac{x}{\xi}\right) + \ldots\right\}$$
$$+x\sum_{q,\bar{q}} e_q^2 \int_x^1 \frac{d\xi}{\xi} g(\xi,Q^2) \left\{\frac{\alpha_S}{2\pi} C_g^{\overline{\rm MS}}\left(\frac{x}{\xi}\right) + \ldots\right\} .$$

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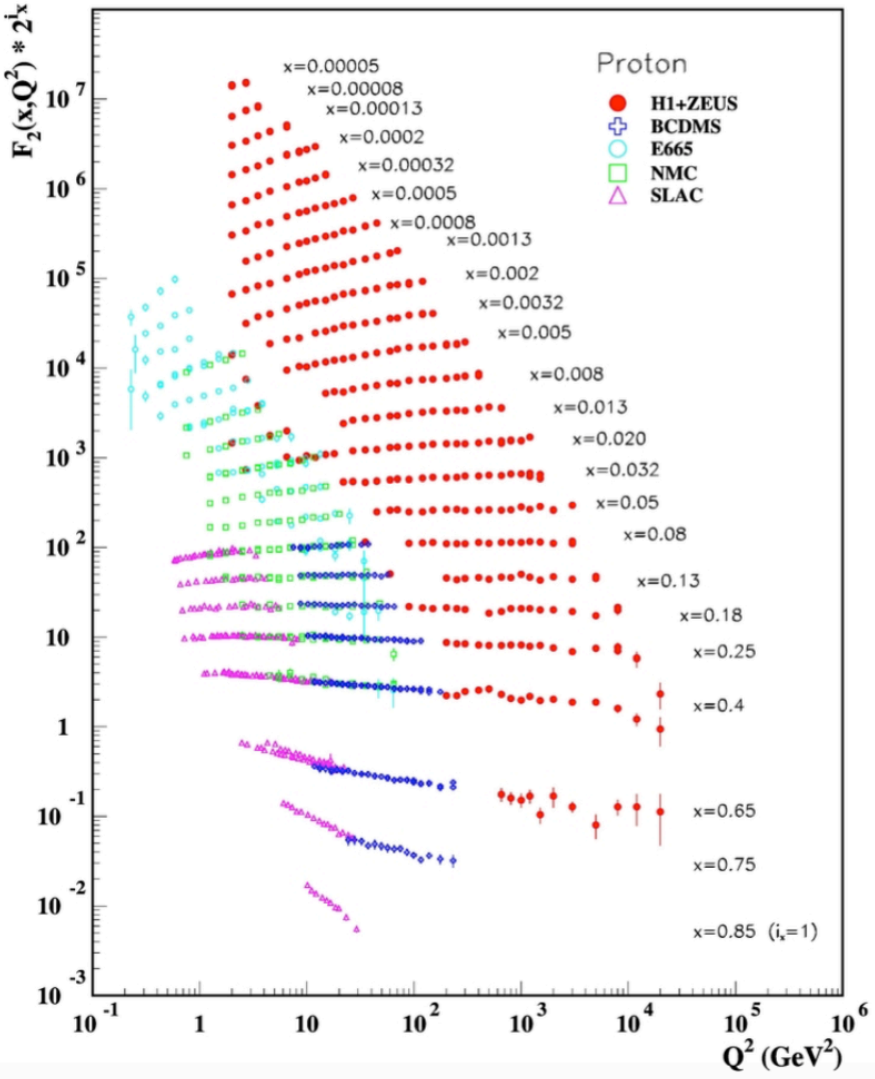
Coefficient functions
(known. depend on renormalization scheme, etc.)

QCD corrections to DIS

$$F_2(x,Q^2) = x\sum_{q,\bar{q}} e_q^2 \int_x^1 \frac{d\xi}{\xi}\, q(\xi,Q^2)\left\{\delta(1-\frac{x}{\xi}) + \frac{\alpha_S}{2\pi}C_q^{\overline{\rm MS}}\left(\frac{x}{\xi}\right)+\ldots\right\}$$
$$+x\sum_{q,\bar{q}} e_q^2 \int_x^1 \frac{d\xi}{\xi}\, g(\xi,Q^2)\left\{\frac{\alpha_S}{2\pi}C_g^{\overline{\rm MS}}\left(\frac{x}{\xi}\right)+\ldots\right\}.$$

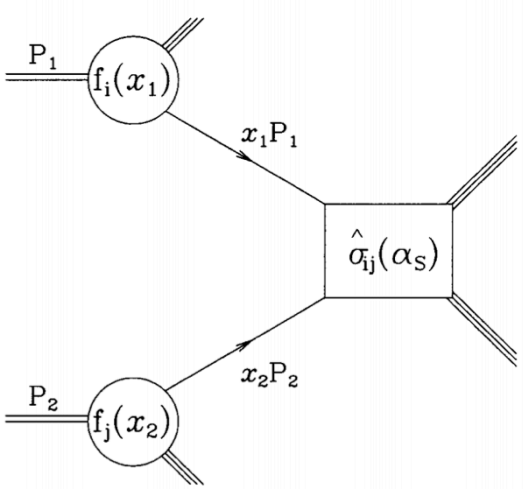
- We do learn something about the gluon PDF from DIS experiments!
- But this is not ideal:
  - Gluon PDF does not show up at leading order

Summary of DIS Experiments



- Can see the dependence of the structure function F_2 on x and Q^2
- PDFs are extracted from cross section measurements
  - e.g. H1 and ZEUS at the ep collider HERA

PDFs at hadron-hadron colliders

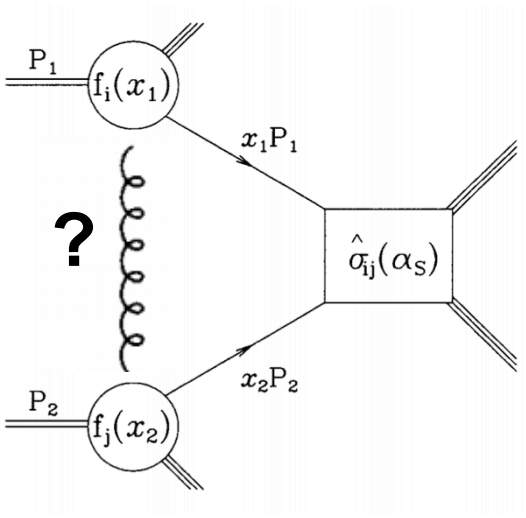


- Total cross section can be determined from PDFs and cross section of underlying process

$$\sigma(P_1, P_2) = \sum_{i,j} \int dx_1 dx_2 \; f_i(x_1, \mu^2) f_j(x_2, \mu^2) \; \hat{\sigma}_{ij}(p_1, p_2, \alpha_S(\mu^2), Q^2/\mu^2).$$

PDFs at hadron-hadron colliders

- If we measure PDFs in ep and pp collisions, do we expect them to agree?
  - Do strong interactions between hadrons distort the PDFs?



PDFs at hadron-hadron colliders

- If we measure PDFs in ep and pp collisions, do we expect them to agree?
  - Do strong interactions between hadrons distort the PDFs?
- These interactions give corrections ~ powers of m^2/E_{CM}^2
  - Ok to neglect these at high energies
- So PDFs will be the same in ep and high energy pp experiments

PDFs from jet production

- Processes resulting in two jets:

$$qq \to qq \qquad \bar{q}\bar{q} \to \bar{q}\bar{q}$$
$$q\bar{q} \to gg \qquad q\bar{q} \to q\bar{q}$$
$$gq \to gq \qquad g\bar{q} \to g\bar{q}$$
$$gg \to q\bar{q} \qquad gg \to gg$$

PDFs from jet production

- Processes resulting in two jets:

$qq \to qq$ $\quad$ $\bar{q}\bar{q} \to \bar{q}\bar{q}$

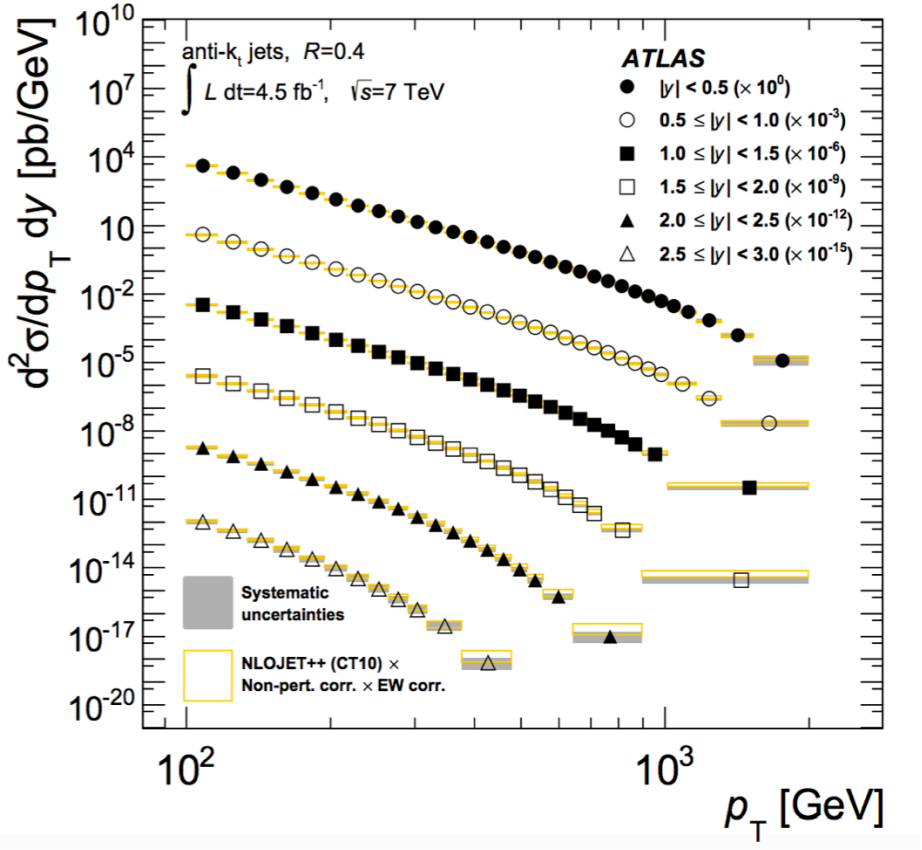
$q\bar{q} \to gg$ $\quad$ $q\bar{q} \to q\bar{q}$

$gq \to gq$ $\quad$ $g\bar{q} \to g\bar{q}$ $\quad$ Initial states with gluons

$gg \to q\bar{q}$ $\quad$ $gg \to gg$

- The gluon PDF enters at leading order!
- Can experimentally measure inclusive jet cross section and learn about $g(x, \mu^2)$

Inclusive jet cross section

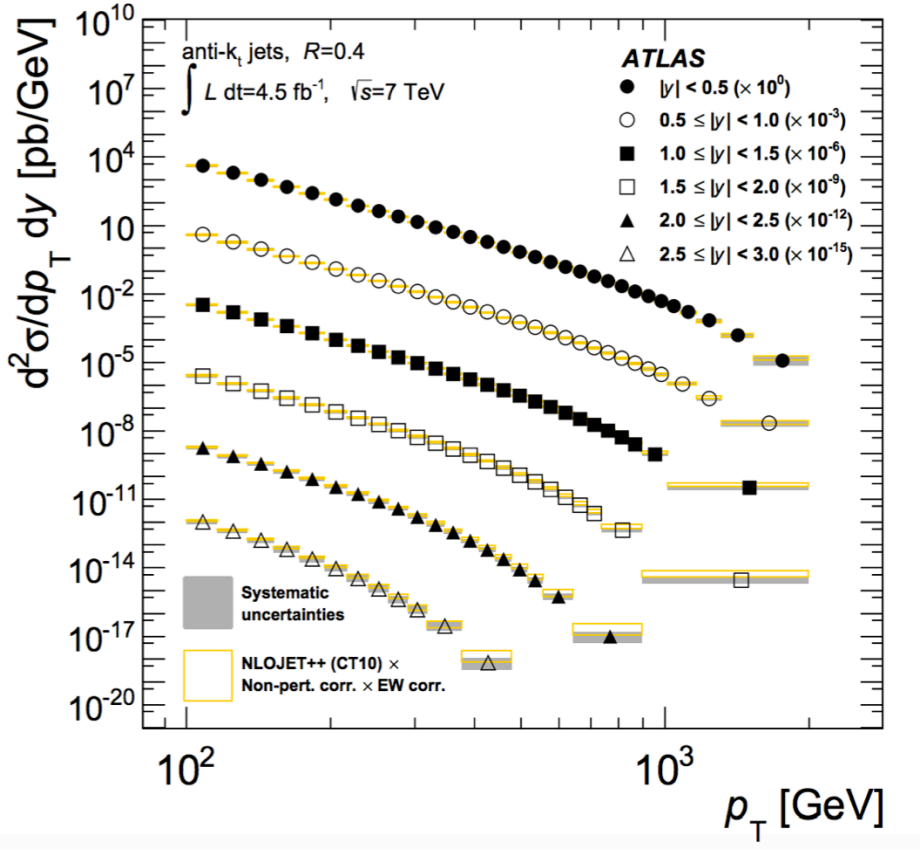


Measurement from ATLAS at 7 TeV

- Why inclusive?

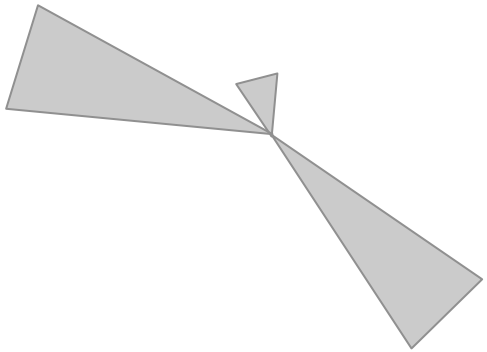
22

Inclusive jet cross section



Measurement from ATLAS at 7 TeV

- Why inclusive?
- Is this 2 jets or 3?

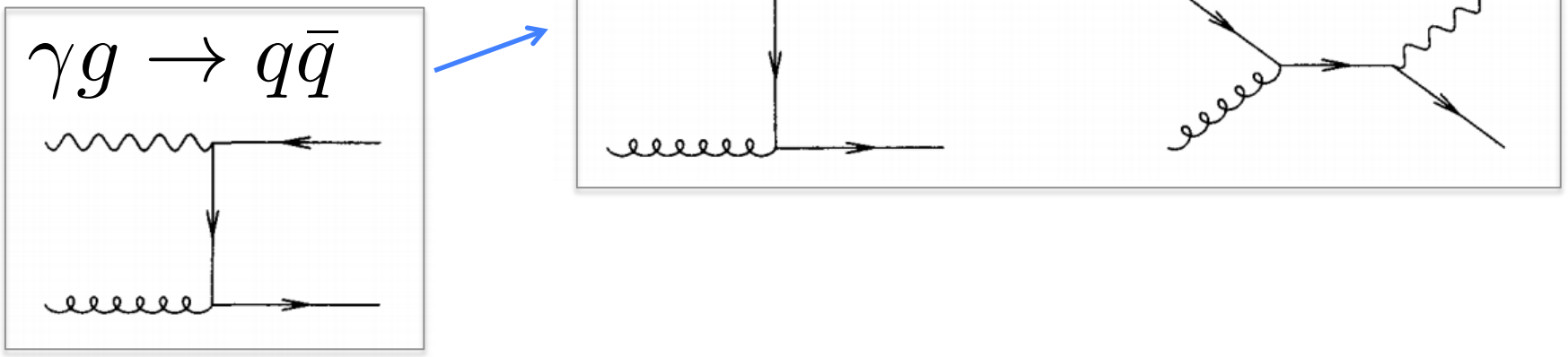


- For the inclusive cross section, it doesn't matter if you're wrong

23

Prompt photon production

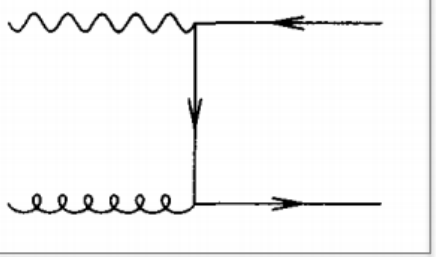
- Try flipping the diagram that was most useful for DIS!



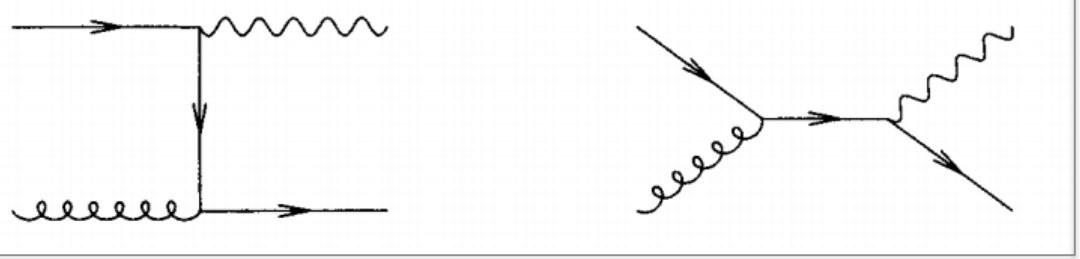
Prompt photon production

- Try flipping the diagram that was most useful for DIS!

$\gamma g \to q\bar{q}$



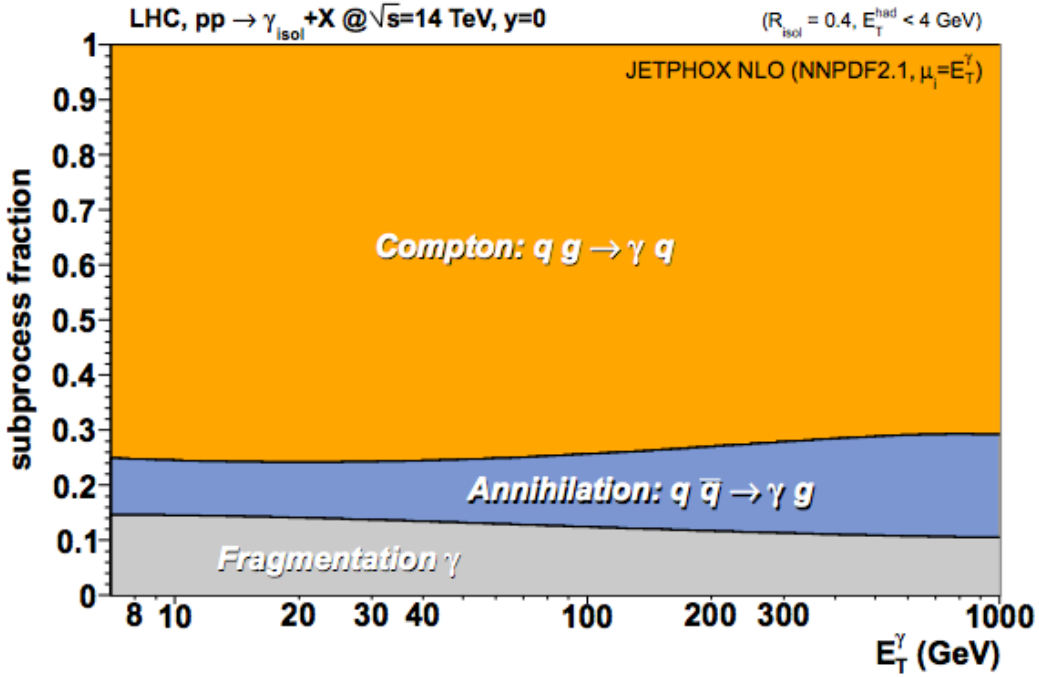
$gq \to \gamma q$



$q\bar{q} \to \gamma g$

Prompt photon production

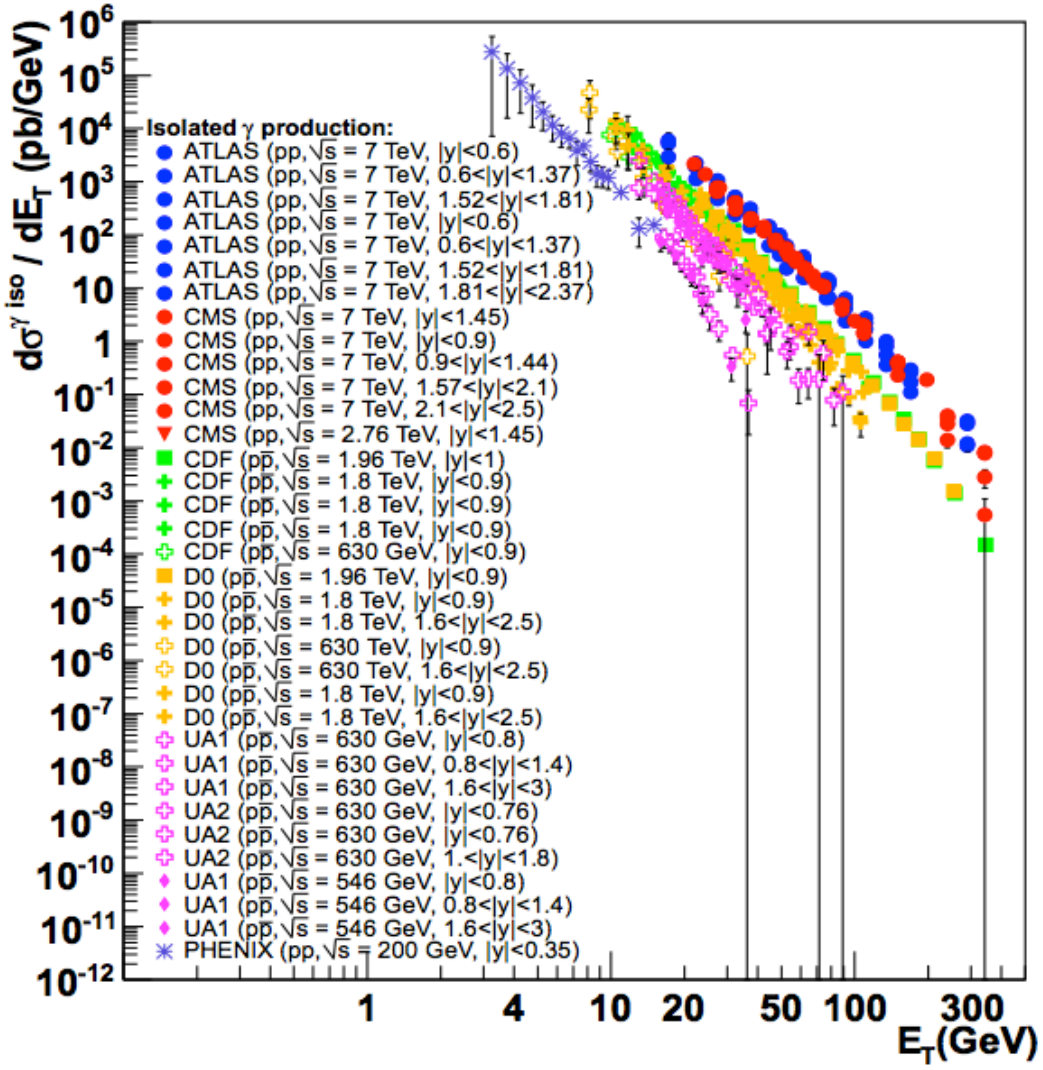
- Relative contribution of prompt photon processes at the LHC at 14 TeV
  - The useful one dominates!



ATLAS prompt γ search at 7 TeV

- Look for events containing one photon
- The photon must be
  - Energetic enough: photon E_T > 100 GeV
  - Isolated: extra E_T inside a cone of size ΔR = 0.4 around the photon must be < 7 GeV
  - In the barrel or end-cap ($|\eta|<1.37$ or $1.52<|\eta|<2.37$), where the electromagnetic calorimeter can measure the energy most accurately
- Main background is light mesons decaying to photons, such as π^0

Measurements of prompt photon cross section at hadron-hadron colliders



Extracting PDFs from data

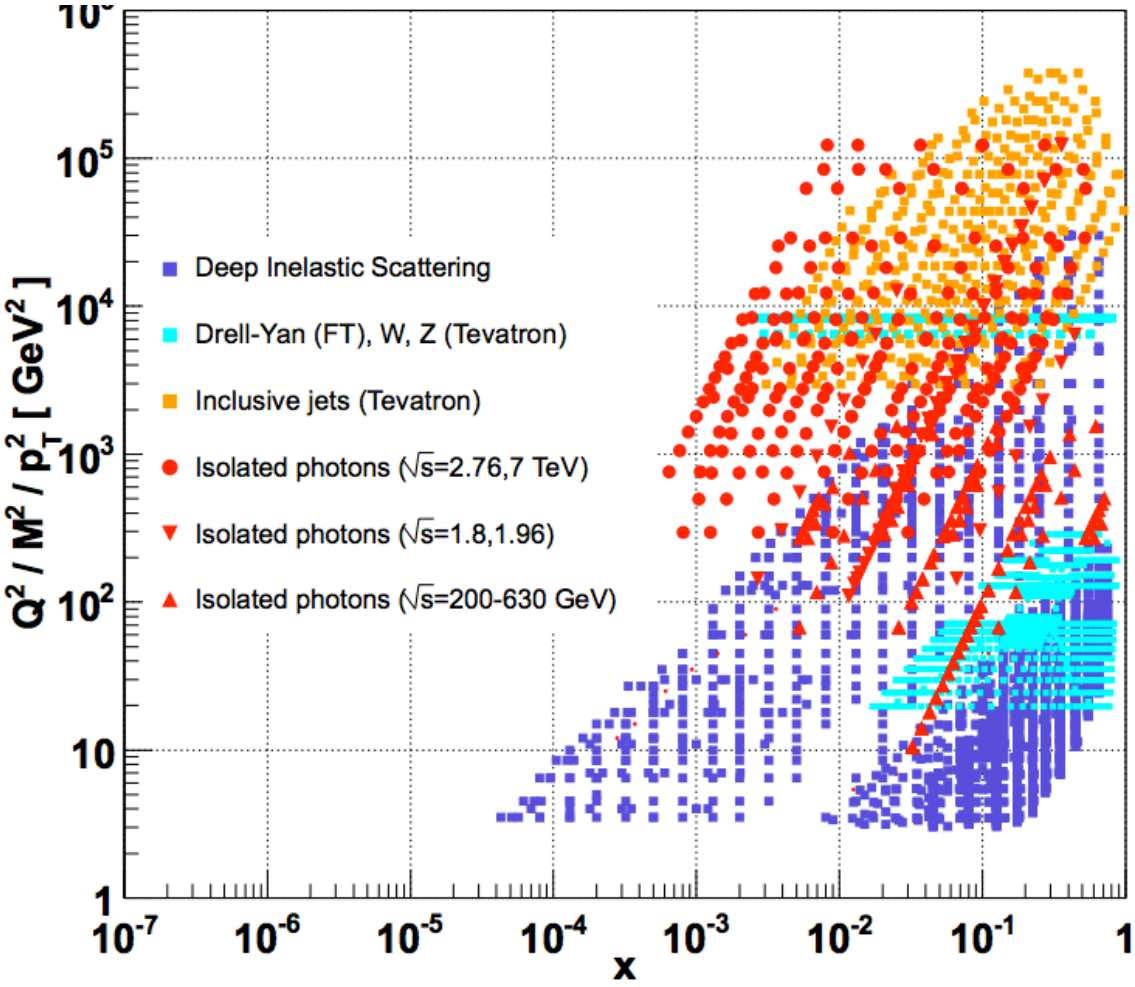
- Assume a functional form for the PDFs, and then fit to cross section data

$$f_i(x, \mu^2) = A_0 x^{A_1} (1-x)^{A_2} P_i(x; A_3, ...)$$

for P_i some smooth function

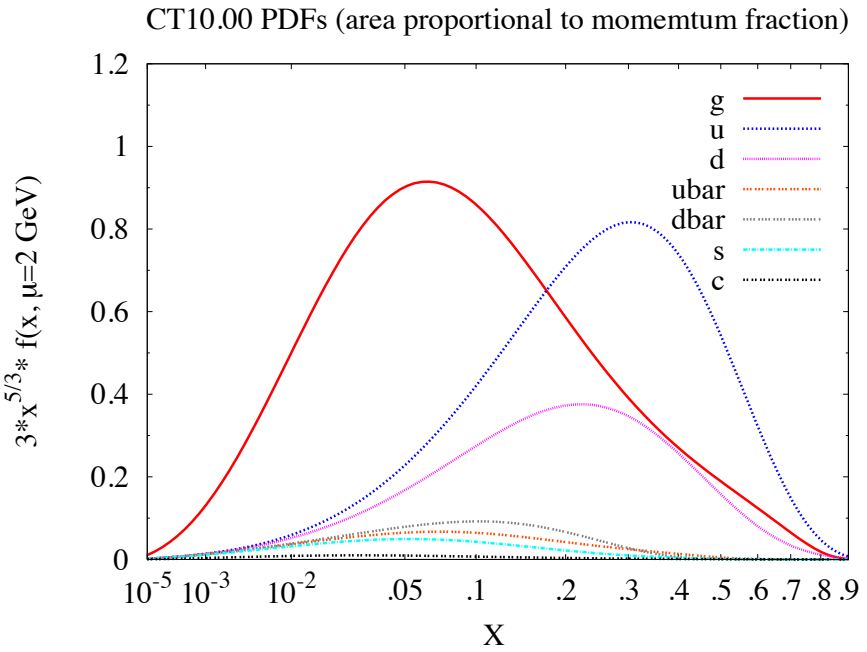
- I won't talk about the statistics magic that is required to accomplish:
  - Fitting to data from many experiments
  - Getting uncertainties out of these fits

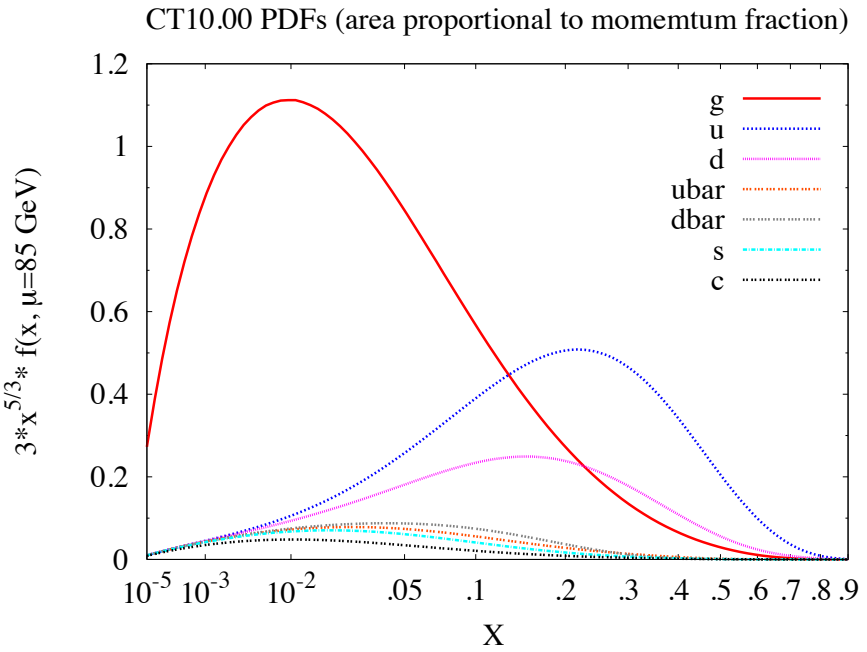
Regions in x, Q^2 (μ^2) where different experiments are useful for determining PDFs



Modern PDF sets

- Many groups have done these fits and put forward sets of PDFs
- All find that the gluon dominates at low x, especially at high μ^2





Modern PDF sets

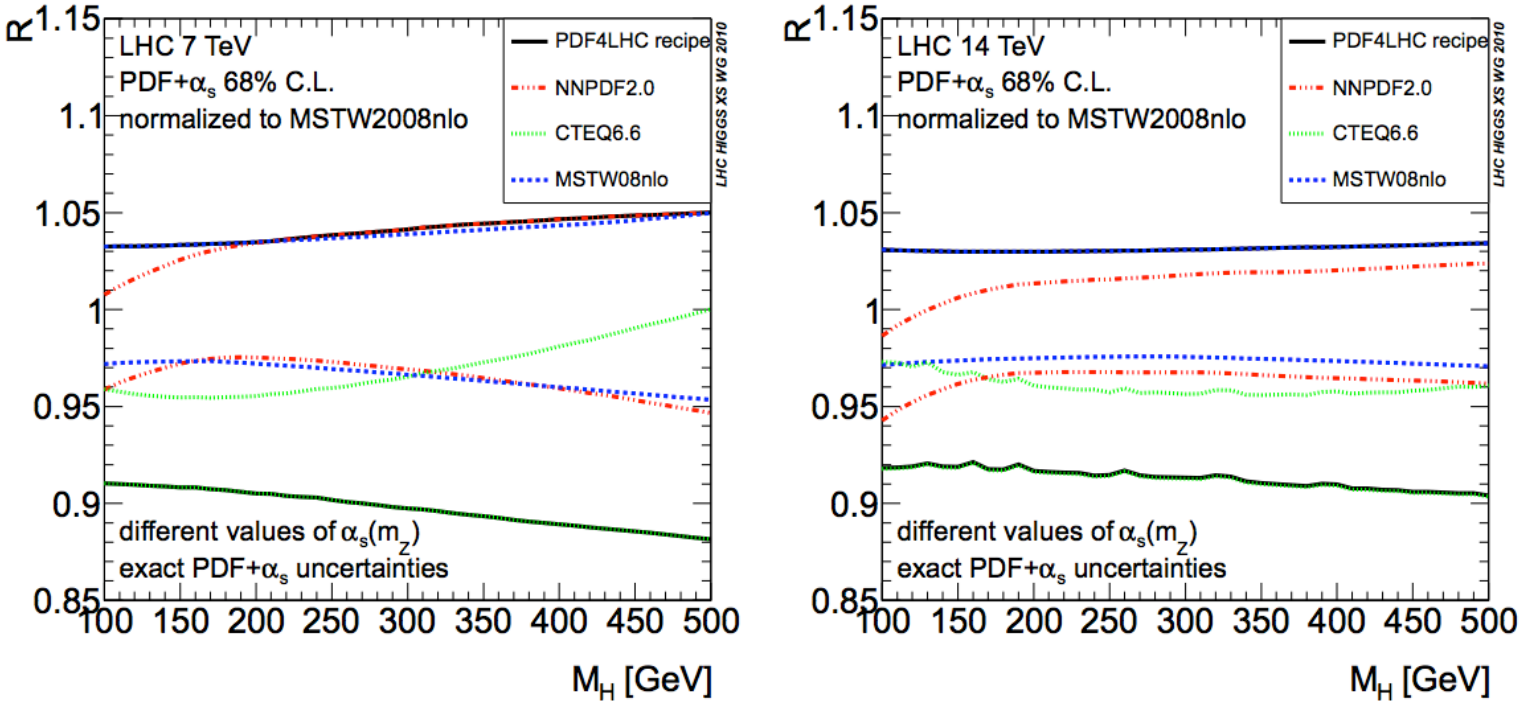
- Many PDF sets are available here for use in Monte Carlo simulations:
  - https://lhapdf.hepforge.org/pdfsets.html
- These PDF sets differ in many ways:
  - Functional form of the PDFs
  - Number of parameters in the fit
  - What data is used in the fits
  - Order in perturbation theory
  - Details of the statistical methods

PDF uncertainties

- Some factors contributing to the PDF uncertainty:
  - Uncertainties from input data from many experiments (not always consistent!)
  - Uncertainty on values of physical parameters (especially α_S, also heavy quark masses, etc.)
  - Order in perturbation theory

PDF uncertainties: an example

- Uncertainties on the cross section of Higgs production via gluon fusion
- Bands shown are combined PDF+α_S uncertainty for several PDF sets



Summary

- We need PDFs (and uncertainties) if we want to make accurate predictions!
- We get information about the gluon PDF by measuring cross sections of
  - Deep inelastic scattering
  - Jet production
  - Prompt photon production
- Modern PDF sets are obtained by fitting data from these experiments

References

- R. K. Ellis, W. J. Stirling, and B. R. Webber, *QCD and collider physics*. Cambridge Univ. Press, Cambridge, UK, 1996.
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